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13. ABSTRACT (Maximum 200 words)

Fabrication technology and device sizes have reached the point where fluctuations on the atomic level may affect device performance. The need for a tool to characterize these structures has been satisfied by cross-sectional scanning tunneling microscopy (XSTM). This summary and attached thesis detail the development and application of XSTM to III-V heterostructures accomplished during the term of the JSEP Fellowship of Warren Wu. An ultra-high vacuum (UHV) system dedicated to XSTM was specifically designed and constructed as part of this work. Reported for the first time were XSTM cross-sections of self-assembled InAs quantum dots, XSTM cross-sections of quantum wires created by the strain-induced lateral-layer ordering (SILO) process as well as the first XSTM data on working device structures. These working device structures include resonant tunneling diode (RTD) structures, a quantum well infrared photodetector structure and a modulation doped field effect transistor (MODFET) structure. XSTM has proved useful in characterizing interface roughness, alloy fluctuations and individual atomic positions.

14. SUBJECT TERMS
cross-sectional scanning tunneling microscopy, XSTM, scanning tunneling microscopy, STM, quantum dots, quantum wires, strain-induced lateral-layer ordering, SILO, resonant tunneling diode, RTD, modulation doped field effect transistor, MODFET

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Executive Summary

Under the JSEP program, a chamber dedicated to cross-sectional scanning tunneling microscopy (XSTM) was constructed for the investigation of cleaved III-V heterostructures. Key points in the design of the chamber were ease of use, low internal surface area and low ultimate pressure. The chamber designs and results acquired after the construction of the chamber are contained in the Ph.D. dissertation of Warren Wu, JSEP Fellow from 1993-1996, from the University of Illinois (see attachment), and this report summarizes some of the key findings.

Once the chamber was completed in early 1996, XSTM investigations of samples from various collaborators began. One of the first results out of the new chamber was an image of a static random access memory (SRAM) structure, provided by H. Goronkin, S. Tehrani and R. Tsui at Motorola,[1,2] which showed that strained materials could be cleaved and successfully imaged.

Soon after, quantum well infrared photodetector (QWIP) structures, from Professor G. Stillman, D. Sengupta and H.-C. Kuo at the University of Illinois, were imaged. In addition to confirming the presence of the quantum wells, XSTM data exhibited an asymmetry between the normal and inverted interfaces, noted in earlier work done under JSEP.[3,4] Also, evidence of As-incorporation in the growth of subsequent layers was observed. These results have been accepted for publication.[5,6]

Next, studies in interface roughness and alloy clustering were performed on modulation-doped field effect transistors (MODFETs), supplied by Professor L. Eastman, G. Martin and M. Seaford at Cornell University in conjunction with Wright Patterson AFB. Phase separation was seen in InAlAs at all growth temperatures, but had a striated look at lower temperatures. One

paper has been accepted for publication,[7] and one has been submitted for presentation at the 24th Conference on the Physics and Chemistry of Semiconductor Interfaces.[8]

For the first time, quantum wires (QWRs) grown by the strain-induced lateral-layer ordering (SILO) process were imaged by XSTM. These samples were provided by Professor K.-Y. Cheng and his students, S.T. Chou, A. Chen and D. Wohlert at the University of Illinois. XSTM provided direct confirmation of the lateral segregation of In-rich and Ga-rich regions during short period superlattice (SPS) growth, previously only analyzed by TEM.

Also for the first time, cross-sections of self-assembled InAs quantum dots were obtained by XSTM. These samples were supplied by Professor J. Harris, Jr. and G. Solomon at Stanford University. InAs islands form on GaAs during the Stranski-Krastanov growth mode, and when multiple layers are grown, subsequent islands vertically align on top of lower dots. The wetting layer on which the islands form was found to be non-continuous and evidence of In between islands above the wetting layer was seen. A paper is currently being drafted.[9]

Following is a list of collaborators and a list of publications.

Researchers

Warren Wu, JSEP Fellow
John R. Tucker, Advisor

Collaborators

Name	Institution	Focus
Professor J.W. Lyding	University of Illinois	developed the STM used in these experiments
S. Skala	University of Illinois	former student of J.W. Lyding, helped perform XSTM experiments on RTD from TI
Professor K.-Y. Cheng	University of Illinois	provided AlGaAs/GaAs superlattice test structures and QWR samples
S. T. Chou	University of Illinois	former student of K.-Y. Cheng
A. Chen	University of Illinois	former student of K.-Y. Cheng
D. Wohlert	University of Illinois	student of K.-Y. Cheng
Professor G. Stillman	University of Illinois	provided QWIP structures
D. Sengupta	University of Illinois	former student of G. Stillman, provided QWIP structure
H.-C. Kuo	University of Illinois	student of G. Stillman, provided series of samples with different growth interrupt sequences
A. Seabaugh	Texas Instruments	provided InGaAs/InP RTD structure
E. A. Beam III	Texas Instruments	provided InGaAs/InP RTD structure
D. Jovanovic	Texas Instruments	provided InGaAs/InP RTD structure
H. Goronkin	Motorola	provided SRAM structure
S. Tehrani	Motorola	provided SRAM structure
R. Tsui	Motorola	provided SRAM structure
Professor L. Eastman	Cornell University	advisor of M. Seaford
M. Seaford	Cornell University	grew InP-based InAlAs/InGaAs MODFETs as well as custom structures
G. Martin	Cornell University	grew AlGaAs/InGaAs strained MODFETs
Professor J. Harris, Jr.	Stanford University	provided InAs quantum dot stack samples
G. Solomon	Stanford University	former student of J. Harris

Publications

1. Warren Wu, John R. Tucker, Glenn Solomon, and James S. Harris, Jr., "Atom-resolved scanning tunneling microscopy of vertically ordered InAs quantum dots" to be submitted.

2. M.L. Seaford, W. Wu, D.H. Tomich, K.G. Eyink, J.R. Tucker, and L.F. Eastman, "Subnanometer Analysis of MBE-grown Ternary Arsenides" submitted for presentation at the 24th Conference on the Physics and Chemistry of Semiconductor Interfaces.

3. M. Seaford, S. Massie, D. Hartzell, G. Martin, W. Wu, J. Tucker, and L. Eastman, *J. Elec. Mater.*, accepted for publication.

4. D.K. Sengupta, S.L. Jackson, W. Wu, J.I. Malin, H.C. Kuo, D. Ahmari, A. Moy, K.C. Hsieh, K.-Y. Cheng, H. Chen, J.R. Tucker, M. Feng, G.E. Stillman, Y.C. Chang, L. Lin, and H.C. Liu, "Growth and characterization of InP/InGaAs p-quantum well infrared photodetector with extremely thin quantum wells" submitted to *J. Appl. Phys.*

5. D.K. Sengupta, J.I. Malin, S.L. Jackson, W. Fang, W. Wu, H.C. Kuo, C. Rowe, S.L. Chuang, K.C. Hsieh, J.R. Tucker, J.W. Lyding, M. Feng, G.E. Stillman, and H.C. Liu, "Comparison of n- and p-type InGaAs/InP quantum well infrared photodetectors" to be published in *MRS Proceedings: Compound Semiconductor Electronics and Photonics*, Spring 1996.

6. W. Wu, S.L. Skala, J.R. Tucker, J.W. Lyding, A. Seabaugh, E.A. Beam, III, and D. Jovanovic, *J. Vac. Sci. Technol. A* **13**, 603 (1995).

7. S.L. Skala, W. Wu, J.R. Tucker, J.W. Lyding, A. Seabaugh, E.A. Beam, III, and D. Jovanovic, *J. Vac. Sci. Technol. B* **13**, 660 (1995).

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[2] S. Tehrani, J. Shen, H. Goronkin, G. Kramer, R. Tsui, and T.X. Zhu, *IEEE Electron Device Lett.* **16**, 557 (1995).

[3] W. Wu, S. Skala, J.R. Tucker, J.W. Lyding, A. Seabaugh, E.A. Beam III, and D. Jovanovic, *J. Vac. Sci. Technol. A* **13**, 602 (1995).

[4] S. Skala, W. Wu, J.R. Tucker, J.W. Lyding, A. Seabaugh, E.A. Beam III, and D. Jovanovic, *J. Vac. Sci. Technol. B* **13**, 660 (1995).

[5] D.K. Sengupta, J.I. Malin, S.L. Jackson, W. Fang, W. Wu, H.C. Kuo, C. Rowe, S.L. Chuang, K.C. Hsieh, J.R. Tucker, J.W. Lyding, M. Feng, G.E. Stillman, and H.C. Liu, "Comparison of n- and p-type InGaAs/InP quantum well infrared photodetectors" to be published in *MRS Proceedings: Compound Semiconductor Electronics and Photonics*, Spring 1996.

[6] D.K. Sengupta, S.L. Jackson, W. Wu, J.I. Malin, H.C. Kuo, D. Ahmari, A. Moy, K.C. Hsieh, K.Y. Cheng, H. Chen, J.R. Tucker, M. Feng, G.E. Stillman, Y.C. Chang, L. Lin, and H.C. Liu, "Growth and characterization of InP/InGaAs p-quantum well infrared photodetector with extremely thin quantum wells" submitted to *J. of Appl. Phys.*

[7] M. Seaford, S. Massie, D. Hartzell, G. Martin, W. Wu, J. Tucker, and L. Eastman, *J. of Elec. Mater.*, accepted for publication.

[8] M.L. Seaford, W. Wu, D.H. Tomich, K.G. Eyink, J.R. Tucker, and L.F. Eastman, "Subnanometer Analysis of MBE-grown Ternary Arsenides" submitted for presentation at the 24th Conference on the Physics and Chemistry of Semiconductor Interfaces.

[9] Warren Wu, John R. Tucker, Glenn Solomon, and James S. Harris, Jr., "Atom-resolved scanning tunneling microscopy of vertically ordered InAs quantum dots" to be submitted.